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ORIGIN OF INDOCHINITE TEKTITES

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The origin of the small, curiously shaped glassy objects named tektites[1] has eluded scientists for nearly two hundred years. Because these objects appeared to be unrelated to the rocks and pebbles with which they were associated, many workers considered them to be meteorites. Evidence has been uncovered in Southeast Asia in connection with a study of the indochinite group of tektites, and specifically with the variety of tektites known as the Muong Nong-type, which shows that the indochinites are terrestrial in origin.

The Muong Nong-type of tektite glass was first described by Lacroix[2] from a locality a few kilometers south of Muong Nong, Laos, where the tektites occurred at a depth of about 1 meter. In an area of about 100 square meters, 67.5 kg of tektites were recovered, the largest piece weighing 3.2 kg. The blocky chunks at this locality are unlike the splash forms common in other tektite groups; yet Lacroix found this glass to have the other properties of tektites.

One of the chief aims of this investigation on tektites, supported by the National Science Foundation, was to visit the type area of the Muong Nong-type tektites. By the time the project was under way, Laos was closed to travel, but fortunately the Geological Survey Division, Royal Department of Mines, Thailand, knew of deposits of both normal and Muong Nong-type tektites in northeastern Thailand and were amenable to a cooperative project to study their field relations. In addition to the three Muong Nong-type deposits previously known by the Geological Survey Division, the authors found a fourth locality. We found also that Muong Nong-type tektites in some localities are scattered over the surface with normal-type tektites. A fifth locality of Muong Nong-type tektites was found at Dalat, and, as in Thailand, scattered fragments of the Muong Nong-type were found with normal indochinites. In Cambodia, Muong Nong-type indochinites were found scattered with normal indochinites in the vicinity of Kratié. Such tektites were also identified in collections from the Philippines and Texas.

A petrographic study of this material and of type specimens from Laos reveals: (1) a plane to folded internal lamination shown by variation from layer to layer in color and content of bubbles and lechatelierite, (2) a shimmery appearing linear structure within the laminae apparently produced by elongation of the melt products of mineral grains, and (3) lack of over-all internal tensional strain.

The occurrence in place, in areas a yard or two across, of as much as 20 kg of chunky tektite glass also differs from the manner in which normal tektites occur. Both types are of almost identical chemical composition and both are related chemically to the lateritic soil from which the Muong Nong-type tektite was excavated. Petrographic and other evidence is advanced in favor of an interpretation that the central part of the strewn-field was hotter than its margins, but no impact crater has been recognized. From this, it is possible to deduce that the indochinites may be the result of a head-on impact with a diffuse object such as a comet, as suggested by Urey,[3] or that they originated through some nuclear or electrical phenomenon not yet visualized.

Mode of Occurrence.—One of the deposits examined, near Phang Daeng, Thailand, was in laterite confined to an area of but a few square meters, beneath about 0.3 m of soil. The chunky tektite material revealed by excavation was roughly lens-shaped, and although the material was broken, with laterite separating the pieces, it was generally grouped together as a mass such as might have congealed from a puddle of molten materials. Ten kg or so of tektites were excavated from the site and perhaps as many more had been recovered previously and sent to the Royal Department of Mines. Test pits were dug along lines intersecting at right angles on the deposit, but no additional tektites were found. However, within 100 m to a kilometer of the deposit several dozen ordinary tektites and a few fragments of the

Muong Nong-type were found on a thin covering of soil formed on Triassic sandstone, which is the dominant rock of the area.

Another Muong Nong-type deposit was visited near Kan Luang Dong, Thailand. Here tektites dug from a depth of 2 m in a well were from a mound-like deposit described as resembling a low white-ant hill. A portion of this mound is reported to remain in the side of the well but circumstances prevented removing the water and mud, therefore the tektites could not be studied in place. However, the 10 kg or so of tektites sorted from the sandy clay on the dump and obtained from the villagers are coated by sandy clay and are free of adhering laterite, showing that this occurrence is not associated with laterite.

Of the two remaining Muong Nong-type tektite localities in Thailand, one, at Nong Sapong, was revealed by a track worn down 0.7 m to the laterite layer where the tektites repose in a small area; the other, 81 km west of Nakhon Sakhon, was in laterite 0.7 m below the surface, exposed as a result of highway construction. In Thailand, therefore, the Muong Nong-type tektites in three cases out of four were associated with laterite formed in place.

The tektites are chemically similar to the laterite if the changes that take place during laterization are considered. This is taken as evidence that the tektites were present before laterization. Laterite, a mixture of oxides of iron and alumina with other substances which have a wide range in quantity, occurs commonly as porous, reddish concretionary crusts, residual from weathering in tropical and subtropical latitudes under conditions of good drainage and marked seasonal rainfall. The present chemical composition of both laterite and tektites is consistent with derivation of the laterite from an original surface material having a composition identical with that of the Muong Nong-type tektites. Changes in the composition of the surficial material since the tektites formed can be determined by comparison with the composition of the tektites (Table 1). We can therefore conclude that the climate in Southeast Asia when the indochinites formed was relatively dry and that the surficial materials from which tektites formed were not leached. After their fusion to a glassy state, some were transported and buried; others—especially the Muong

TABLE 1

CHEMICAL ANALYSES OF MUONG NONG-TYPE TEKTITES AND ASSOCIATED LATERITE AND SOIL, PHANG DAENG, THAILAND

	Muong Nong-Type Tektites Lightest colored	Muong Nong-Type Tektites Darkest colored	Laterite with tektites (depth 9–11 in.)	Laterite (depth 30 in.)	Soil (depth 4–6 in.)
Sample No. →	158177	158172	158178	158174	158175
SiO_2	76.9	80.4	45.8	50.9	84.6
Al_2O_3	10.6	9.5	12.2	12.8	5.4
TiO_2	0.67	0.62	0.54	0.59	0.45
Fe_2O_3	0.60	0.45	29.6	25.3	4.7
FeO	3.3	3.0	0.04	0.12	0.14
MnO	0.08	0.08	0.66	0.06	0.01
MgO	1.6	1.3	0.44	0.46	0.35
CaO	1.6	1.1	0.06	0.08	0.12
Na_2O	1.4	1.2	0.08	0.10	0.04
K_2O	2.3	2.2	0.86	1.2	0.60
H_2O^-	—	—	—	—	—
H_2O^+	0.24	0.14	9.3	8.2	3.1
P_2O_5	0.12	0.10	0.17	0.10	0.06
Total	99	100	100	100	100

Analyzed by Paul Elmore, Ivan Barlow, Samuel Botts, and Gillison Chloe, of the U.S. Geological Survey, using analytical methods similar to those described in the U.S. Geological Survey Bulletin 1036-C.

Nong-type—were buried in place beneath surficial materials. The climate later became seasonally much more humid, resulting in leaching of surficial materials soluble in tropical ground waters, downward movement and precipitation of iron in the insoluble oxidized state, and leaching and removal of more soluble constituents. Before or during laterization, the Muong Nong-type tektite glass became fractured, and etching took place, accompanied by deposition of laterite along fractures and in etch pits.

The Muong Nong-type indochinite is now known from 48 km west of Khon Kaen, Thailand, southeastward for a distance of 830 km to Dalat, Viet Nam, and in a southwest-northeast direction for more than 500 km from Kompong Speu, Cambodia, to Muong Nong, Laos. If systematic collecting were to be done, the area of occurrence would surely be extended.

Chemistry.—If, as postulated, the Muong Nong-type tektites are the result of local fusion of the ground to puddles of melted glass, then chemical analyses of the tektites should compare with analyses of the material around them, provided no change has taken place in these materials since the tektites formed. But laterization has taken place since they formed, which implies chemical change of the material since the tektites formed. During laterization, iron was leached and precipitated downward, alumina remained the same, hydration took place, and other constituents were leached and carried away.

Although the two analyses of Muong Nong-type tektites in Table 1 have little resemblance to the analyses of the laterite associated with them or the laterite 20 inches deeper, by using the Muong Nong-type tektite as a standard of comparison the changes which are thought to have taken place can be shown. In Table 2, the

TABLE 2

CHEMICAL CHANGE INVOLVED TO PRODUCE LATERITE IF THE SOURCE MATERIAL WAS OF THE SAME COMPOSITION AS THE MUONG NONG-TYPE TEKTITES AT PHANG DAENG, THAILAND

	A Laterite associated with tektites, analysis 158178	B Laterite associated with tektites, recalculated moisture free	C Average of tektite analyses 158177 and 158172	D Original amount present on basis of no change in Al_2O_3 (C × 1.34)	E Gains and losses in per cent of original amount present (B × 100/D)
SiO_2	45.8	50.6	78.65	105.4	48
Al_2O_3	12.2	13.5	10.05	13.5	100
TiO_2	0.54	0.60	0.64	0.86	70
Fe_2O_3	29.6	32.75	0.52	0.70	4,600
FeO	0.04	0.04	3.15	4.24	1
MnO	0.66	0.73	0.08	0.10	730
MgO	0.44	0.49	1.45	1.95	25
CaO	0.06	0.07	1.35	1.82	4
Na_2O	0.08	0.09	1.3	1.75	5
K_2O	0.86	0.95	2.25	3.03	31
H_2O	9.3	—	0.19	—	—
P_2O_5	0.17	0.19	0.11	0.15	127

laterite associated with the tektites (column A) is calculated to a dry basis (column B) and the average of the two tektite analyses from Table 1 is given in column C. Since Al_2O_3 is neither lost nor gained in the process of laterization and since it is more abundant in the laterite than in the tektites, an over-all loss of constituents by a factor of 1.34 must have taken place. If the amount of each constituent in column C is multiplied by the factor 1.34 (recorded in column D) and is compared with column B, the gains and losses can be shown in per cent of the original amount present (column E).

Fe_2O_3 has been enriched 46-fold, MnO 7-fold, P_2O_5 slightly, Al_2O_3 is constant, and all other constituents have been depleted in various amounts from slightly for TiO_2 to about half for SiO_2, three-quarters for K_2O and MgO to one-twentieth or less for Na_2O and CaO, and one-hundredth for FeO. These are exactly the kinds of changes that take place during laterization, and these results favor the laterite's forming from material of the composition of the Muong Nong-type tektites. The tektites survived even though half the silica was dissolved from the source materials of the laterite. The reason for this is that the source materials are fine grained and offer many times more surface area for attack than do the relatively large chunks of tektite.

The same comparison was made between the Muong Nong-type tektite and the laterite 20 in. beneath. It was found that iron is less abundant, manganese is unchanged, and leaching is less. The soil overlying the tektites shows no chemical similarity either to the laterite or to the Muong Nong-type tektites, suggesting that it is a recent accumulation of sandy material.

TABLE 3

CHEMICAL CHANGE INVOLVED TO PRODUCE LATERITE IF THE SOURCE MATERIAL WAS OF THE SAME COMPOSITION AS THE MUONG NONG-TYPE TEKTITE AT NONG SAPONG, THAILAND

	A Laterite associated with tektites, analysis 158179	B Laterite associated with tektites, recalculated moisture free	C Muong Nong-type tektite, analysis 158176	D Original amount present on basis of no change in Al_2O_3 (C × 0.97)	E Gains and losses in per cent of original amount present—(B × 100/D))
SiO_2	37.5	41.2	71.4	69.4	58
Al_2O_3	12.7	13.9	14.3	13.9	100
Fe_2O_3	39.3	43.1	0.50	0.49	8,800
FeO	0.07	0.08	4.5	4.4	2
MgO	0.05	0.05	2.1	2.0	2
CaO	0.05	0.05	1.9	1.8	3
Na_2O	0.08	0.09	1.5	1.5	6
K_2O	0.60	0.66	2.7	2.6	25
H_2O	8.9	—	—	—	—
TiO_2	0.58	0.64	0.84	0.82	78
P_2O_5	0.15	0.16	0.16	0.16	100
MnO	0.05	0.05	0.10	0.10	50

Analyses 158176 and 158179 by Paul Elmore, Ivan Barlow, Samuel Botts, and Gillison Chloe, of the U.S. Geological Survey, using analytical methods similar to those described in the U.S. Geological Survey Bulletin 1036-C.

TABLE 4

CHEMICAL CHANGE INVOLVED TO PRODUCE LATERITIC CLAY AT DEPTH OF 6 FEET IN WELL IF THE ORIGINAL MATERIAL WAS OF THE SAME COMPOSITION AS THE MUONG NONG-TYPE TEKTITE AT NONG SAPONG, THAILAND

	A Clay beneath tektites, analysis 158173	B Clay beneath tektites, recalculated moisture free	C Muong Nong-type tektite, analysis 158176	D Original amount present on basis of no change in Al_2O_3 (C × 1.15)	E Gains and losses in per cent of origina amount present (B × 100/D)
SiO_2	63.9	69.2	71.4	82.4	84
Al_2O_3	15.2	16.5	14.3	16.5	100
Fe_2O_3	10.5	11.4	0.50	0.58	2,300
FeO	0.14	0.15	4.5	5.2	3
MgO	0.28	0.30	2.1	2.4	12
CaO	0.08	0.09	1.9	2.2	4
Na_2O	0.13	0.14	1.5	1.7	8
K_2O	1.2	1.3	2.7	3.1	42
H_2O	7.1	—	—	—	—
TiO_2	0.81	0.88	0.84	0.97	91
P_2O_5	0.06	0.06	0.16	0.18	33
MnO	0.02	0.02	0.10	0.12	17

Analyses 158173 and 158176 by Paul Elmore, Ivan Barlow, Samuel Botts, and Gillison Chloe, of the U.S. Geological Survey, using analytical methods similar to those described in the U.S. Geological Survey Bulletin 1036-C.

The same comparisons have been made in Table 3 of Muong Nong-type tektites rom Nong Sapong, Thailand, and associated laterite, and in Table 4 of Muong Nong-type tektites and sandy clay from a depth of 6 feet in a nearby well. The results obtained are about the same as found at Phang Daeng, except that there is a lesser amount of leaching of the underlying sample at Nong Sapong.

The manner of occurrence of the Muong Nong-type indochinites, their internal properties, and their chemical properties as related to the material in which they lie, all point to their formation by fusion of the ground. The decisive evidence of the terrestrial origin of indochinites is furnished by the analyses in Table 5. In this

TABLE 5

CHEMICAL ANALYSES OF MUONG NONG-TYPE AND NORMAL-TYPE INDOCHINITES, THAILAND

	Normal tektite 48 km west of Khon Kaen	Muong Nong-type tektite Phang Daeng	Normal tektite Phang Daeng	Muong Nong-type tektite Phang Daeng
Number →	61-1034	61-1031	61-1032	61-1033
SiO_2	72.77	72.44	73.86	73.50
Al_2O_3	13.37	13.34	12.57	12.59
TiO_2	0.78	0.76	0.71	0.74
Fe_2O_3	0.37	0.29	0.23	0.41
FeO	4.34	4.29	4.00	4.03
MnO	0.10	0.10	0.076	0.094
MgO	2.00	2.00	1.98	1.93
CaO	2.01	2.16	2.24	2.16
Na_2O	1.48	1.61	1.62	1.58
K_2O	2.40	2.48	2.32	2.45
H_2O^-	0.03	0.01	0.00	0.00
H_2O^+	0.07	0.11	0.11	0.10
P_2O_5	0.04	0.11	0.08	0.15
Total	99.76	99.70	99.80	99.73
Ni, ppm	25	31	24	32

Analyzed by C. O. Ingamells, Mineral Constitution Laboratories, College of Mineral Industries, The Pennsylvania State University, University Park, Pennsylvania.

table, two analyses of Muong Nong-type indochinites and two of normal-type indochinites are paired. A glance shows that each pair is almost identical, and that both tektite types probably came from the same material.

Other Features of the Indochinite Strewn-Field.—Given such strong presumptive evidence that the Muong Nong-type indochinites formed by fusion of the ground and their identity in composition to normal-type indochinites, other features of the strewn-field deserve examination for their bearing on the origin of the indochinites.

Lechatelierite particles were found to vary in amount from locality to locality within the indochinite strewn-field, being much more abundant in the peripheral areas. This difference may be explained by greater heat and a longer period of heating in the central area (northeast Thailand and adjacent Cambodia and Laos), causing relatively more lechatelierite to diffuse into the surrounding glass and disappear. That this may be true is supported by the relatively smaller size of the lechatelierite particles from the central area, its smoother appearance, and the lesser abundance of bubbly lechatelierite.

It is thought that the bubbles associated with lechatelierite are formed from the gas and liquid-filled vacuoles which are so common in quartz, and that a study of these bubbles may give additional information on the relative temperature of formation of the various tektite groups. In the case of bubble-free lechatelierite, the viscosity would have been so low that all gas escaped. In the case of the lechatelierite with associated bubbles, it seems likely that the fluidity was just sufficient for the gas of the vacuoles to coalesce but that the viscosity was too great for the bubbles so formed to escape. In the case of the frothy lechatelierite, it seems likely that the viscosity was still higher and that the gas in the vacuoles expanded but did not coalesce.

The possibility is not ruled out that the lechatelierite content of the indochinites is related to the local soil and rock on which they lie rather than to the strewn-field as a whole, but if this were true, it would not explain the low content of lechatelierite of the tektites found on the broad outcrop of Triassic sandstone in the central area, or other properties of the lechatelierite indicating high temperatures in the central area.

"Fingers" in tektites were recently described by Barnes[4] for the first time and illustrated.[5] These "fingers," mostly more silicic (rarely less silicic) than the enclosing tektite glass, or schlieren with some characteristics of "fingers" have now been found in every tektite group except the javaites, billitonites, and Ivory Coast tektites where relatively few specimens have been available for study. "Fingers" were first seen in australites as light-colored, narrowly elongated inward extensions up to several millimeters long which are represented on the surface by protuberances. Their resistance to etching and the low index of refraction indicate that they are more siliceous than the surrounding glass. Moreover, when viewed while being rotated on a universal stage, they are seen to be coated with tiny particles that appear to be segregated lechatelierite. These particles are mostly at the intersections of very low but fairly sharp ridges with their crests toward the tektite glass. Some of these particles are so tiny that it is uncertain whether they are actually lechatelierite or are instead an optical effect caused by the intersecting ridges. It is thought that these "fingers" could have been formed only at high temperatures by volatilization of other constituents concentrating the silica.

Iron has a boiling point of 3,000°C, and its presence has a marked positive effect on the refractive index of a glass of which it is a part. Tektites contain a few per cent of iron, and since the "fingers" are markedly lower in refractive index than is the remainder of the tektite, it appears that iron volatilized along with other constituents as the silica was concentrated. Tektites with this kind of "finger" probably formed at temperatures in excess of 3,000°C. "Fingers," and schlieren with some of the properties of "fingers," in addition to their abundance in australites are rather common in indochinites and philippinites and were found in one moldavite.

Recently, "fingers" of a different character have been found which are darker than the surrounding glass, have a higher refractive index, have smooth surfaces without lechatelierite, and end in pits at the surface of the tektite. These "fingers" probably were produced by volatilization at temperatures lower than the boiling point of iron, causing iron to be enriched. Several were seen in indochinites from China and one is present in a bediasite.

"Fingers" provide evidence of temperature variations within the indochinite strewn-field. The indochinites from China near the margin of the strewn-field contain dark "fingers" indicative of temperatures of formation below 3,000°C, whereas those in the central part of the strewn-field contain light-colored "fingers" indicative of temperatures of formation above 3,000°C. Thus, evidence derived from variations in the content and appearance of lechatelierite, of bubble and froth content, and of the presence and nature of "fingers" all leads to the same conclusion: whatever the causal agent may have been, temperatures produced were higher in a broad area in the central part of the strewn-field, falling off toward its margin.

From the shapes of bubbles some deductions also can be made as to the cooling history of tektites and related glasses. Spherical bubbles show that the glass was not being deformed while it cooled, whereas elongate bubbles show that deformation was taking place. Bubbles in the Muong Nong-type tektite are predominantly elliptical, probably as a result of slow flowage of the glass as it cooled. Specimens with spherical and elongate bubbles are about equally numerous in normal indochinites. Many of the normal indochinites are flattened forms (plates and disks), and these may have fallen to the ground while still plastic enough to flatten, stretching the bubbles as they did so.

Conclusions.—A study of the internal features of the Muong Nong-type indochinites and of their chemical composition, as compared with the lateritic materials with which they are associated, furnishes strong evidence that they are the result of fusion of the ground before laterization. That the Muong Nong-type and normal-type tektites were formed by the same event is supported by the identical chemical composition of the two. Evidence from regional variation in nature and number of lechatelierite particles, bubbles, and "fingers" in normal-type indochinites indicates that a large area in the central part of the strewn-field was hotter than the margins, and information from bubble shapes indicates that many splash forms fell back to earth while still plastic.

None of this evidence is compatible with an extra-terrestrial origin for the indochinites, and little of it is consistent with their origin from the impact of a large meteorite or asteroid. The occurrence of two types of tektites so dissimilar in internal structure and outward appearance yet so similar in chemical composition could hardly represent a single extra-terrestrial shower, especially when one type is concentrated in the middle portion of their field of scatter. No evidence of an impact crater to which they might be attributed has been found, and if one had been found it would still be difficult to visualize the manner in which the Muong Nong-type glass could have segregated out according to temperature from the splash of a point impact.

Although impact glasses and tektites appear to form a continuous series, different members of the group may have been formed in different ways. Those showing evidence of two-stage melting such as could result from transit through the atmosphere (e.g., australites and javaites) are easier to explain by assigning an extra-terrestrial origin to them. Some, such as those from the San Francisco del Monte site in Manila, thought to be weathering out of tuff, may be the result of dense body impact of such force as to trigger a volcanic eruption[6] and produce a great caldera such as that of Taal. And others, such as the bediasites, moldavites, and perhaps the bulk of the philippinites, may have an origin similar to that of the indochinites.

The evidence is against an extra-terrestrial source or origin by dense body impact for the indochinite strewn-field. It could be explained, however, by the head-on impact of a diffuse object such as a comet[3] is thought to be or by some yet unvisualized and therefore uninvestigated nuclear or electrical phenomenon.

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*ROTATION OF THE CRYSTAL LATTICE IN KINK BANDS, DEFORMATION BANDS, AND TWIN LAMELLAE OF STRAINED CRYSTALS**

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This paper is concerned with the geometry of rotation of the lattice of any highly strained domain in a deformed crystal with respect to the lattice of the unstrained host crystal. In particular it is a revision of the geometry of external rotation of narrow kink bands, deformation bands, and twin lamellae in experimentally deformed crystals of calcite and of dolomite. The degree and sense of external rotation are correlated with strain and with the orientation and sense of glide in the active glide system. The material studied is a series of single calcite crystals experimentally deformed by D. T. Griggs and H. C. Heard over the period 1952–1961 at the Institute of Geophysics, University of California, Los Angeles.

Correlation of External Rotation and Strain in Deformed Metal Crystals.—Metallurgists have long recognized that in experimental deformation of single crystals, strain is concentrated in local domains such as kink bands, and that the crystal lattice within such a domain becomes progressively rotated with respect to the lattice of the undeformed ends of the specimen, in which a constant orientation is maintained throughout deformation.[1] The same effect has been observed in experimentally deformed crystals of calcite, dolomite, enstatite, and other minerals.[2] Since rotation is measured with reference to coordinates (e.g., lattice directions in the host crystal) external to the rotated domain, it is, in Sander's terminology, an external rotation (to be distinguished from internal rotation of passive marker planes, such as cleavage cracks, within the deformed domain).

The magnitude and sense of external rotation depend upon (1) the magnitude of strain, (2) the orientation of the active glide system in relation to the axes of principal stress σ_1 and σ_3 and (3) constraint of the undeformed ends of the specimen as determined by the mechanical conditions of loading. In all cases the active glide plane rotates toward the axis of minimal stress σ_3. (In conformity with nomenclature currently in use by students of experimental deformation of rocks, compressive stresses are positive. tensile stresses negative; σ_1 is algebraically greater than